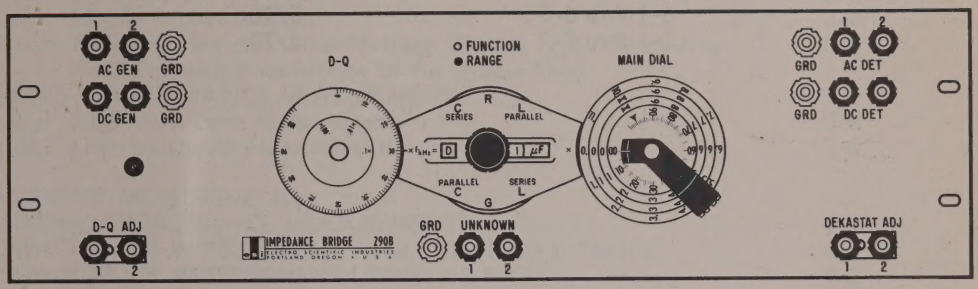
Instruction Manual
MAY 1970

MODEL 290B
IMPEDANCE BRIDGE



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SECTION I
INTRODUCTION

1.1 DESCRIPTION

The ESI Model 290B Impedance Bridge measures resistance, conductance, inductance, and capacitance. It also measures the dissipation factor (D) and the storage factor (Q) of inductors and capacitors.

Resistance and conductance measurements are usually made with direct current because of the increased accuracy and the lack of hum pickup and stray capacitance effects. Resistance and conductance measurements can be made using ac, but they may require external reactance compensation.

Inductance and capacitance measurements are made in terms of a simple two-element circuit with the same impedance as the unknown. The bridge dials read the values of this equivalent circuit. To achieve highest measurement accuracy, an equivalent parallel circuit is used for high Q inductors and high D capacitors. An equivalent series circuit is used for low D capacitors and low Q inductors.

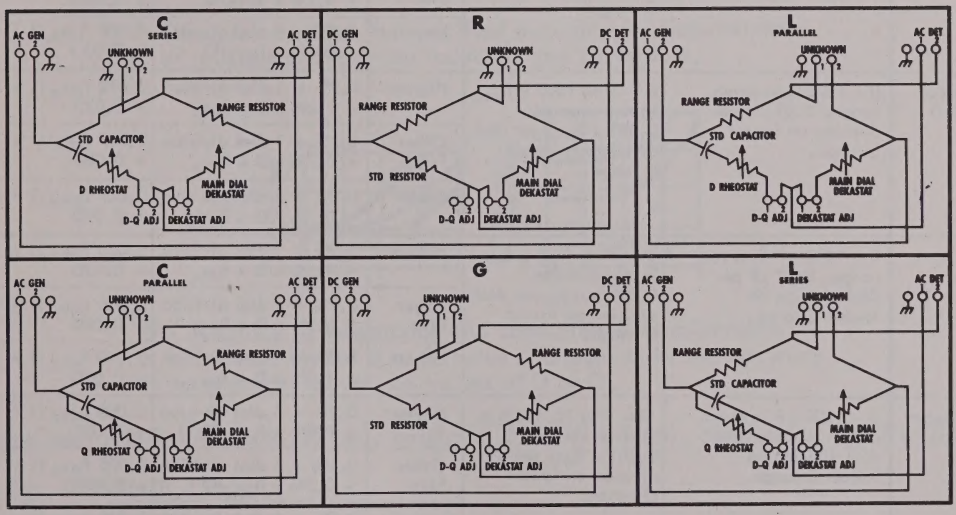


Figure 1-1. Bridge Circuit Diagrams

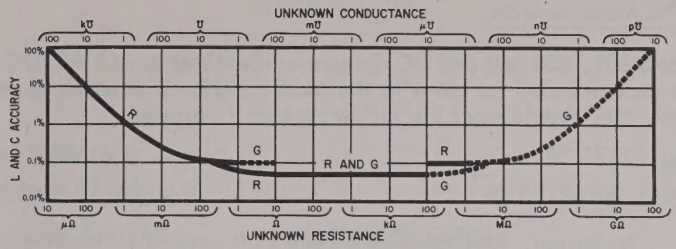
1.2 SPECIFICATIONS

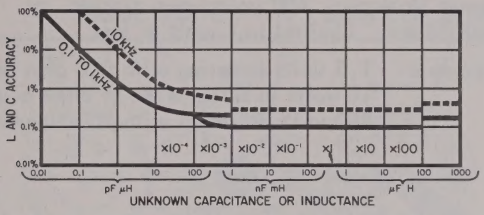
The functions, ranges, and accuracy specifications of the instrument are shown in the following table and graphs.

Function	Ranges		Accuracy*		
	Magnitude	D or Q	L,R,C,G Range	Magnitude	D or Q
Resistance	0 - 1200 kΩ in seven ranges;** 0.01 mΩ per dial division on lowest R range.		Highest	0.1% + 1 dial division	
			Other Five	0.05% + 1 dial division	
			Lowest	0.1% + 1 dial division	
Conductance	0 - 1200 mmhos in seven ranges; 10 pmhos (100 GΩ) per dial division on lowest G range.		Highest	0.1% + 1 dial division	
			Other Five	0.05% + 1 dial division	
			Lowest	0.1% + 1 dial division	
Inductance (Series)	0 - 1200 H in seven ranges; 0.01 μH per dial division on lowest L range.	Q = 0 to 10.5 x f_{kHz} in three ranges; 0.001 x f_{kHz} per dial division on lowest Q range.	Highest	0.2% + 1 dial division + 1.2% x f_{kHz}/Q	0.012 f_{kHz} $(1 + Q^2)$ + 0.02Q
			Other Five	0.1% + 1 dial division + 0.7% x f_{kHz}/Q	0.007 f_{kHz} $(1 + Q^2)$ + 0.02Q
			Lowest	0.2% + 1 dial division + 0.7% x f_{kHz}/Q	0.007 f_{kHz} $(1 + Q^2)$ + 0.02Q
Inductance (Parallel)	0 - 1200 H in seven ranges; 0.01 μH per division on lowest L range.	D = 0 to 10.5 x f_{kHz} in three ranges; 0.001 x f_{kHz} per dial division on lowest D range.	Highest	0.2% + 1 dial division + 1.2% x D x f_{kHz}	0.012 f_{kHz} $(1 + D^2)$ + 0.02D
			Other Five	0.1% + 1 dial division + 0.7% x D x f_{kHz}	0.007 f_{kHz} $(1 + D^2)$ + 0.02D
			Lowest	0.2% + 1 dial division + 0.7% x D x f_{kHz}	0.007 f_{kHz} $(1 + D^2)$ + 0.02D
Capacitance (Series)	0 - 1200 μF in seven ranges; 0.01 pF per dial division on lowest C range.	D = 0 to 10.5 x f_{kHz} in three ranges; 0.001 x f_{kHz} per dial division on lowest D range.	Highest	0.2% + 1 dial division + 0.5% x D x f_{kHz}	0.005 f_{kHz} $(1 + D^2)$ + 0.02D
			Other Five	0.1% + 1 dial division + 0.5% x D x f_{kHz}	0.005 f_{kHz} $(1 + D^2)$ + 0.02D
			Lowest	0.2% + 1 dial division + 1.0% x D x f_{kHz}	0.010 f_{kHz} $(1 + D^2)$ + 0.02D
Capacitance (Parallel)	0 - 1200 μF in seven ranges; 0.01 pF per dial division on lowest C range.	Q= 0 to 10.5 x f_{kHz} in three ranges; 0.001 x f_{kHz} per dial division on lowest Q range.	Highest	0.2% + 1 dial division + 0.5% x f_{kHz}/Q	0.005 f_{kHz} $(1 + Q^2)$ + 0.02Q
			Other Five	0.1% + 1 dial division + 0.5% x f_{kHz}/Q	0.005 f_{kHz} $(1 + Q^2)$ + 0.02Q
			Lowest	0.2% + 1 dial division + 1.0% x f_{kHz}/Q	0.010 f_{kHz} $(1 + Q^2)$ + 0.02Q

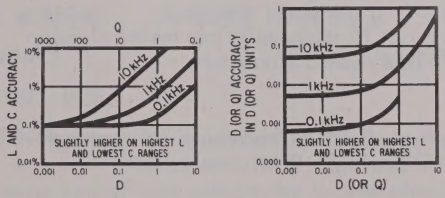
*Accuracy specifications for inductors and capacitors apply for units with reasonably high Q (low D) at frequencies near 1 kHz. Nominal frequency range is 100 Hz to 10 kHz, with slight accuracy derating near the limits.

**Equivalent resistance measurements to 100 GΩ are possible using conductance ranges.





These curves show the specified accuracy for measurements of resistors and low-loss inductors and capacitors.



The accuracy of inductance and capacitance measurements is influenced by the D or Q value. Graphs show the accuracy to be expected at various values of D or Q.

Dimensions: Width 19 in. (48.25 cm), height 5.25 in. (13.3 cm), depth 8 in. (20.3 cm).

Weight: 18.5 lb (8.4 kg).

1.3 ACCESSORIES REQUIRED

1.3.1 For DC Measurements

The ESI Models 801, 803 and 840 DC Generator-Detector or 865 AC/DC Generator-Detector are recommended for use with the Model 290B. If other dc generator and detector units are used, they should meet the following specifications:

DC Generator

Desired characteristics

Isolation: Resistance to ground must exceed 10 terohms (10^{13} ohms).
Maximum Voltage: 400 volts open circuit.
Output Power: Limited to 1 watt or less.

For example: 1.5 volts in series with 0.5 ohm or more
10 volts in series with 25 ohms or more
300 volts in series with 25 kilohms or more

1.3.2 DC Detector

Either a galvanometer or an electronic null detector can be used.

Electronic Null Detector

Desired characteristics

Sensitivity: 10 microvolts per meter division
Noise: Less than 5 microvolts

Galvanometer

Sensitivity: 0.03 microampere per meter division
Critical Damping: 2 kilohms or more

1.3.3 For AC Measurements

The ESI Models 860A or 861A AC Generator-Detector or 865 AC/DC Generator-Detector are recommended for use with the Model 290B. If other dc generator and detector units are used, they should meet the following specifications:

AC Generator

Desired characteristics

Frequency Range: 0.1 kHz to 10 kHz
Output Voltage: 0 to 20 volts open circuit
Series Protective Resistor: 100 ohms or more

AC Detector

Desired characteristics

Sensitivity: 20 microvolts
Input Impedance: 500 kilohms
Harmonic Suppression: 30 dB by 2nd harmonic

SECTION II

OPERATION

2.1 CONTROLS

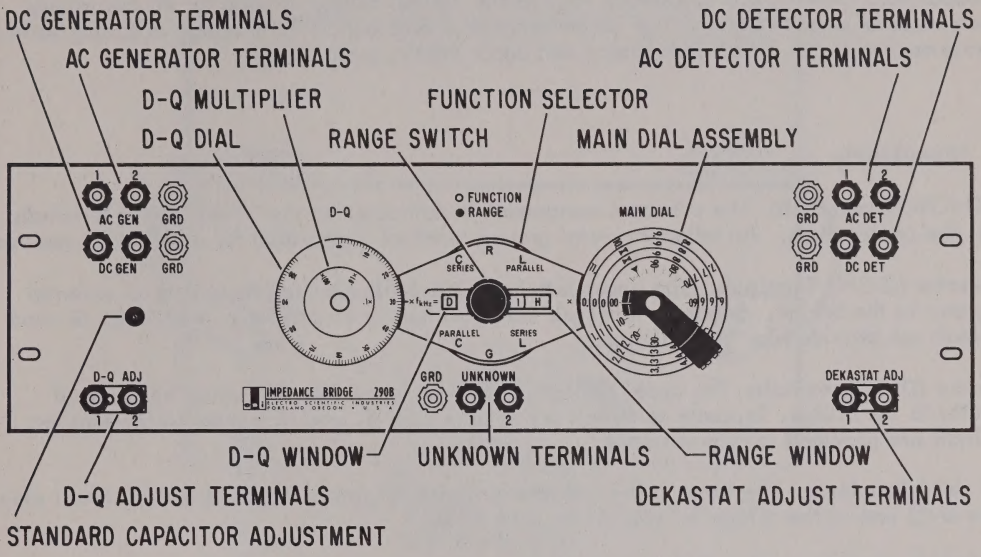


Figure 2-1. Model 290B Controls

FUNCTION Selector: The large center dial selects the bridge circuit configuration and connects the appropriate generator and detector.

Function	Measurement	Generator and Detector
C_s	Series Capacitance	AC
R^s	Resistance	DC
L_p	Parallel Inductance	AC
L^p	Series Inductance	AC
G^s	Conductance	DC
C_p	Parallel Capacitance	AC

The circuit in use is indicated by the mark at the edge of the selector switch. The electrical measurement unit is indicated in the right half of the right-hand window. For L or C measurements, the left-hand window shows whether the dissipation factor (D) or the storage factor (Q) is being measured.

RANGE Switch: The black center knob selects any of seven multipliers ranging from 10^{-4} to 100. The multiplier in use appears in the left half of the right-hand window.

MAIN DIAL Assembly: The right-hand DEKASTAT dial reading times the range multiplier reading gives the value of resistance, conductance, inductance, or capacitance being measured.

D-Q Multiplier: The left-hand black knob selects the D-Q multiplier. The multiplying factor in use appears at the left of the D or Q value .

D-Q Dial: The reading of the large left-hand dial, times the D-Q multiplier reading, times the frequency in kilohertz gives the value of D or Q.

Standard Capacitor Adjustment: To the left of the D-Q Dial is the adjusting screw for the standard capacitor. Setting this adjustment to give the correct bridge reading for an accurately known value of capacitance (0.1 μF recommended) assures a short-term bridge accuracy rating improvement of 0.1% for all inductance and capacitance measurements.

2.2 TERMINALS

UNKNOWN Terminals: The unknown component is connected to the UNKNOWN terminals under the center dials. An adjacent metal ground terminal is provided for a shield connection.

Generator (GEN) Terminals: The upper left-hand terminals are for connecting an external generator to the bridge. Separate terminals are provided for dc and ac connections. Ground terminals are provided for convenience.

Detector (DET) Terminals: The upper right-hand terminals are for connecting an external detector to the bridge. Separate terminals are provided for dc and ac connections. Ground terminals are provided for convenience.

D-Q ADJ Terminals: The lower left-hand terminals are for attaching an external circuit element to the D-Q arm of the bridge for special measurements.

DEKASTAT ADJ Terminals: The lower right-hand terminals are for attaching an external circuit element to the MAIN DIAL DEKASTAT arm of the bridge for special measurements.

SECTION III

RESISTANCE MEASUREMENT

3.1 MEASURING RESISTORS

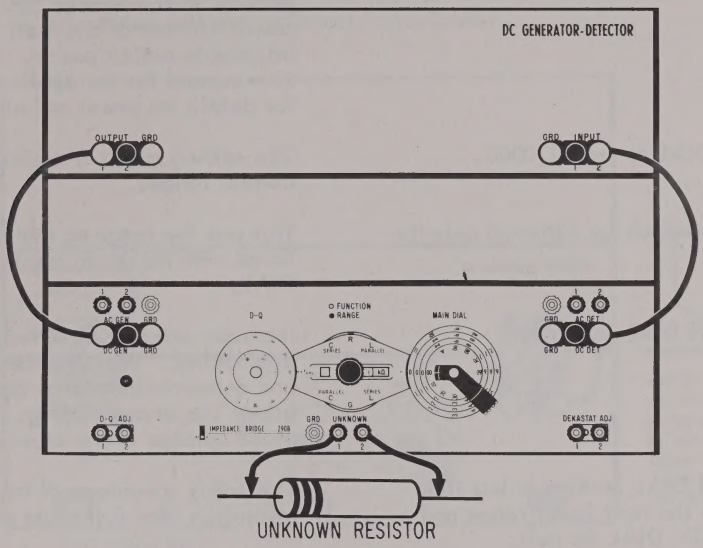


Figure 3-1. Resistance Measurement Connections

1. Connect dc generator and detector.

   Connect the external dc generator and detector to the dc terminals. They will be connected to the correct bridge circuits by the circuit selector.

> **CAUTION:** *Limit the generator output to one watt maximum. Recommended ESI DC Generators and Detectors have this protective feature built in.*

2. Connect resistor to UNKNOWN terminals.

   Make good contact with the terminals.

3. Set FUNCTION selector to R or G.

   $$R \text{ in kilohms} = \frac{1}{G \text{ in millimhos}}$$

   If between 0.83 ohm and 1.2 megohms, measure either RESISTANCE or CONDUCTANCE. If less than 0.83 ohm (>1.2 mho), measure RESISTANCE. If greater than 1.2 megohms (<0.83 micromho), measure CONDUCTANCE.

4. Set power supply voltage and detector sensitivity.	Set the detector sensitivity so that the pointer is about half-way between the center and one end of the scale. Set the generator resistance to give the most detector deflection for any unbalance. Set the generator power for the maximum power that will not harm the device being tested. Recommended ESI generators are power-limited at one watt, and most have adjustable output power. See the instruction manual for the applicable generator for details on power adjustment.
5. Set MAIN DIAL to read 3.0000.	This setting makes it easier to find the correct range.
6. Set RANGE switch for minimum detector signal.	This sets the range so that the value can be found with maximum resolution on the MAIN DIAL.
7. Adjust MAIN DIAL for null.	Increase detector sensitivity as the null is approached. Recommended ESI generators and detectors cannot be damaged by normal bridge use at any setting. Be careful to avoid damage if any other detector is used.
8. If the MAIN DIAL reading is less than 1.2000, use the next lower range and readjust MAIN DIAL for null.	This takes advantage of the increased resolution near full scale of the dial.

3.2 MEASURING AC RESISTANCE

For greatest accuracy resistors should always be measured with dc. The accuracy of ac measurement will be 0.3% for one kilohertz and below over the range from one ohm to one megohm.

The indicated connections for the phase correction capacitor compensate for series inductance or parallel capacitance. It is impossible to separate the correction for the unknown from that for the rest of the bridge circuit. If large reactances are involved the circuit should be measured as a capacitance or inductance and the resistance calculated.

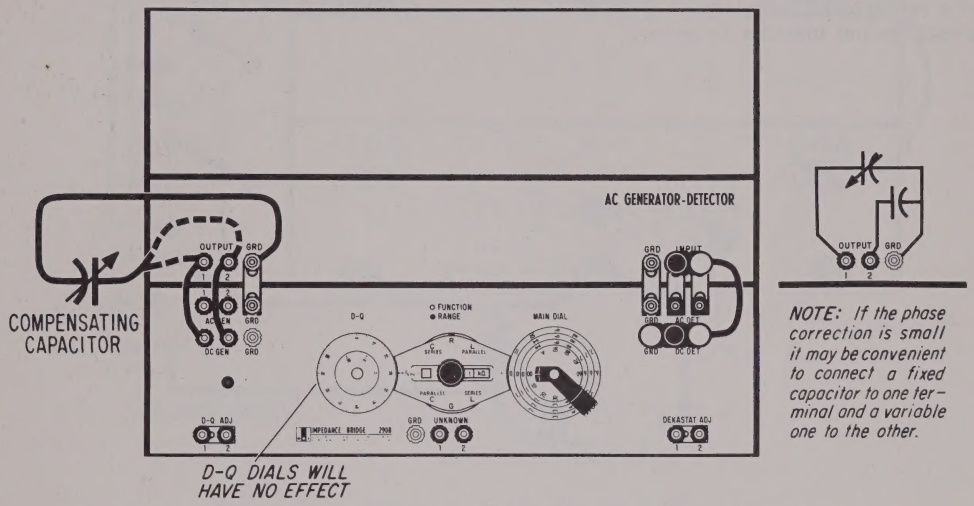


Figure 3-2. AC Resistance Measurement Connections

1. Remove the ac generator connecting straps.	The ac detector straps need not be removed.
2. Connect the bridge DC GEN and DET terminals to the ac generator and detector.	Short lengths of open-wire leads for the generator will minimize errors.
3. Set the FUNCTION selector to R or G.	This connects the desired bridge circuit.
4. Try to balance the bridge as with dc.	Usually the eye will not completely open and/or the meter will not go completely to zero, thus indicating uncompensated phase shift.
5. Connect a variable capacitor from ground to one of the generator terminals and try to obtain a null with it and the MAIN DIALS.	Connecting the capacitor from ground to either generator terminal permits compensation for some of the possible circuits of the unknown.

6. If a null cannot be reached, connect the variable capacitor between the other generator terminal and ground. A null should be obtainable with one connection or the other.

This permits balance over the remaining possible circuit combinations.

If a non-linear element is being measured by ac, a null balance may not be possible because the bridge will not be in balance at all parts of the cycle.

7. The resistance value as read will be correct for equivalent circuits consisting of a resistor and capacitor in parallel or a resistor and inductor in series.

R and G accuracy will be 0.3% or better for resistors between 1 ohm and 1 megohm at a frequency of 1 kHz or less.

3.3 RESISTANCE LIMITS CHECKING

For rapidly checking resistance values between two tolerance limits:

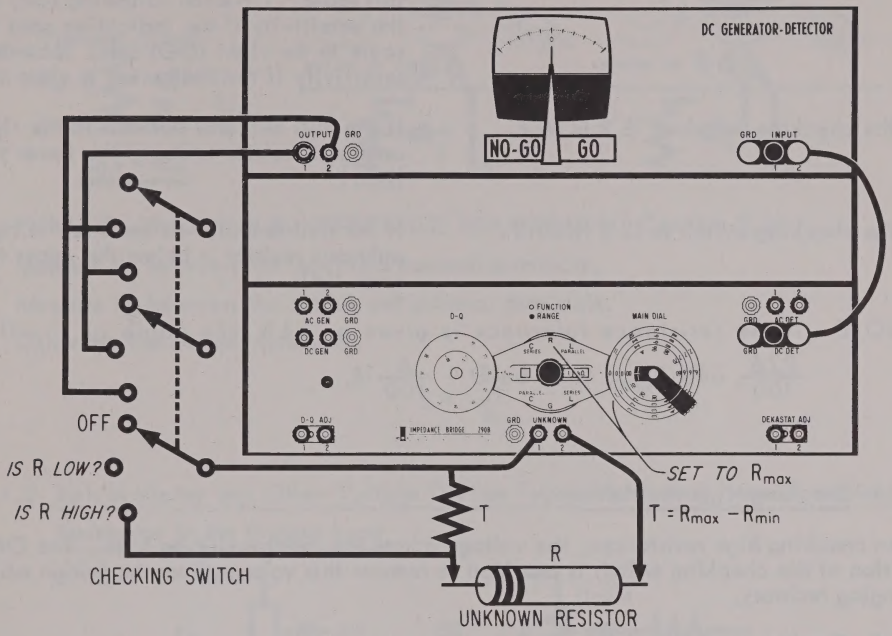


Figure 3-3. Resistance Limits Checking Connections

1. Set the FUNCTION selector to R or G. Set RANGE switch and MAIN DIAL to the upper resistance limit.	These settings will allow checking both upper and lower limits.
2. Connect the circuit as shown.	The generator reversal permits using the same direction of the null detector deflection for GO with both the upper and lower limit.
3. Short the probes together and check the direction of null detector defelction.	The null detector should move to the right when the CHECKING SWITCH is in the IS R LOW? position. If it does not, reverse the polarity of the generator voltage or reverse the connections between the CHECKING SWITCH and the generator.
4. Attach the probes to the unknown resistor.	This completes the bridge circuit.
5. Check the zero position of the null detector.	The zero position may be adjusted by the null detector zero control.

6. Find the optimum sensitivity setting by trial.

Start with minimum sensitivity. On the first resistance check, increase the detector sensitivity until the indication is nearly full scale. On each following test, reduce the sensitivity if the indication goes off scale to the right (GO) side; increase the sensitivity if the indication is close to zero.

7. Set the checking switch to IS R LOW?.

If the null detector deflects to the right the unknown resistor is above the lower tolerance limit.

8. Set the checking switch to IS R HIGH?.

If the null detector deflects to the right the unknown resistor is below the upper tolerance limit.

NOTE: If the resistance tolerance is given as ±Δ%, the value of T will be $\frac{R2\Delta}{100}$ *and* R_{max} *will be* $(1 + \frac{\Delta}{100})R$.

3.3.1 Checking High Resistance

When checking high resistances, the voltage across the resistor will be high. The OFF position of the checking switch is provided to remove this voltage from the bridge while changing resistors.

3.3.2 Checking Low Resistance

When checking low resistances the probe resistance R_o must be taken into account. It can be measured by shorting the probes. The bridge dials should be set to read $R_{max} + R_o$.

Resistance Limits Checking

If

$R_{min} < R < R_{max}$

And if

$T = R_{max} - R_{min}$

Then

$(R_{meas}) < R_{max}$ Only if $R < R_{max}$

$(R_{meas} + T)\ R_{max}$ Only if $R < R_{min}$

If

$R(1 + \Delta) = R_{max}$

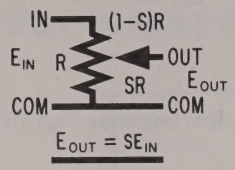
$R(1 - \Delta) = R_{min}$

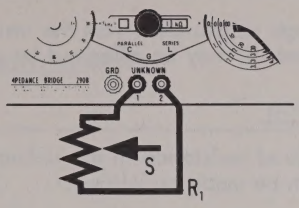
Then

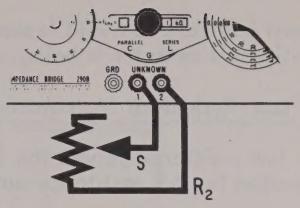
$T = R2\Delta$

3.4 VOLTAGE DIVIDER CHECKING

3.4.1 Simple Tapped Resistor



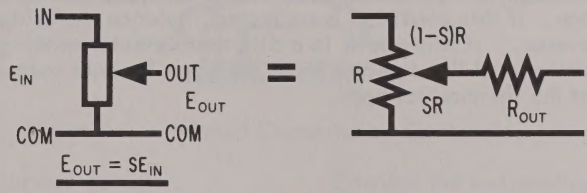


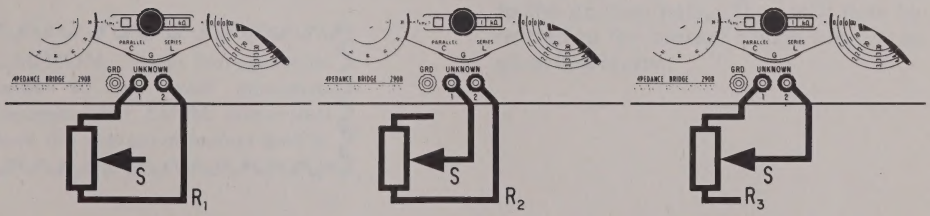


1. Follow the instructions for RESISTANCE MEASUREMENT (Section 3.2).
2. Measure R_1 between the input and common terminals.
3. Measure R_2 between the output and common terminals.
4. Calculate the divider setting S.

$$S = \frac{R_2}{R_1}$$

3.4.2 Kelvin Varley and Other Voltage Divider Types Which May Have Equivalent Resistance in the Output Lead





1. Follow the instructions for RESISTANCE MEASUREMENT (Section 3.2).
2. Measure R_1 between the input and common terminals.
3. Measure R_2 between the output and common terminals.
4. Measure R_3 between the input and output terminals.
5. Calculate the divider setting S.

$$S = \frac{1}{2} + \frac{R_2 - R_3}{2R_1}$$

3.5 NOTES ON RESISTANCE MEASUREMENT

3.5.1 High-Resistance Measurements

Care must be taken to avoid leakage resistance across the unit being measured. If an electronic null detector is being used it may be affected by ac hum picked up by the leads.

3.5.2 Low-Resistance Measurements

On the low resistance ranges the lead resistance in the unknown arm becomes significant. A correction for this resistance can be made as follows:

1. Short the test leads together at the point that they are to be connected to the unknown resistor and measure this zero resistance.

2. Connect the test leads to the unknown resistor and measure the resistance reading.

3. The resistance value of the unknown resistor is the resistance reading minus the zero resistance.

4. If the unknown resistance is to be connected directly to the terminals, the zero resistance reading can be taken by connecting a piece of heavy copper wire between the unknown resistance terminals. (No. 14 AWG copper wire has a resistance of about 0.00025 ohm/inch.)

Sometimes thermal voltages are generated at connections and these can lead to erroneous balances of the bridge. If this condition is suspected, balance the bridge and then set the output switch to "reverse." If this results in a different detector reading, change the MAIN DIAL DEKASTAT setting until the detector reads the same for both output polarities. This cancels the effect of the thermal voltages.

SECTION IV

CAPACITANCE MEASUREMENT

4.1 NORMAL CAPACITANCE MEASUREMENT

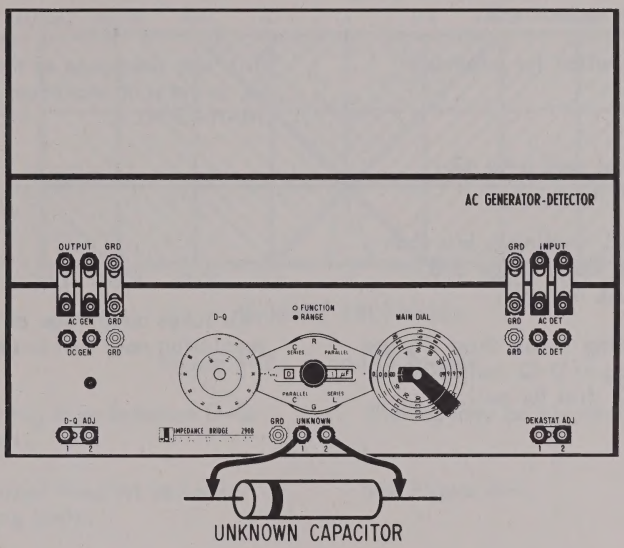


Figure 4-1. Normal Capacitance Connection

1. Connect ac generator and detector.

   Connect the external generator and detector to the ac terminals. They will then be connected to the correct bridge circuits by the circuit selector.

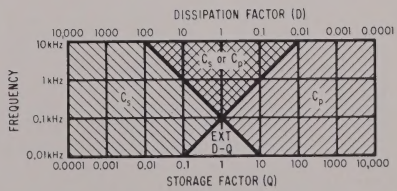
   CAUTION: *Limit the generator output to one watt maximum. Recommended ESI AC Generators have this protective feature built in.*

2. Connect unknown capacitor to UNKNOWN terminals.

   To minimize stray capacitance to ground, connect the outside foil to the left-hand terminal.

3. Set the FUNCTION selector to C_s or C_p.

   At 1 kHz:
   Use C_p for D greater than 0.1.
   Use C_s for D lower than 10.



4. Set generator voltage and detector gain. See CAUTION, step 1.

5. Set MAIN DIAL to read 3.0000.

6. Set D-Q multiplier to .1x. These settings make it easier to find the correct range.

7. Set D-Q dial to 0, if bridge measures D, or 100, if bridge measures Q.

8. Set the RANGE switch for minimum detector signal. This sets the range so that the value can be found with maximum resolution on the MAIN DIAL.

9. Adjust MAIN DIAL and D-Q dial alternately for null.

10. If the MAIN DIAL reading is less than 1.2000, use next lower range and readjust MAIN DIAL for null.

11. If D-Q dial reading is less than 10, use next lower setting of D-Q multiplier and readjust D-Q dial for null. This takes advantage of the increased resolution near full scale of the dial.

4.2 CAPACITANCE MEASUREMENT WITH EXTENDED D RANGE

The D and Q ranges of the bridge can be extended by use of an external rheostat connected to terminals provided. Figure 4-2 shows the ranges for which this technique is necessary. This technique may be used on any range if higher resolution is required than can be obtained with the D-Q dial.

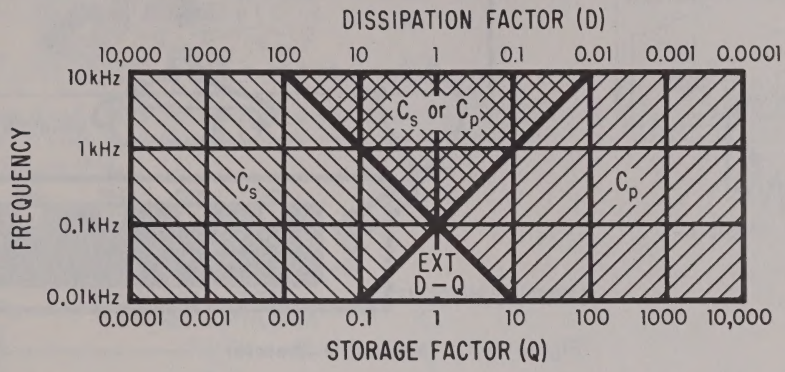


Figure 4-2. D and Q Ranges

1. Remove shorting lug from between D-Q ADJ binding posts.	The lug may be pivoted to one side.
2. Connect an external rheostat between D-Q ADJ binding posts.	See Figure 4-3.
3. Balance the bridge using external rheostat and D-Q dial.	The measured capacitance is the product of the C-R-L dial setting times the setting of the RANGE switch.
4. Calculate D.	D is the dissipation factor.
$D = f_k (0.628 R_k + D_{dial})$	f_k is the frequency in kilohertz.
	R_k is the resistance of the external D rheostat in kilohms.
	D_{dial} is the D-Q dial reading.
	$f_k = 1$ if the internal generator and detector are used.

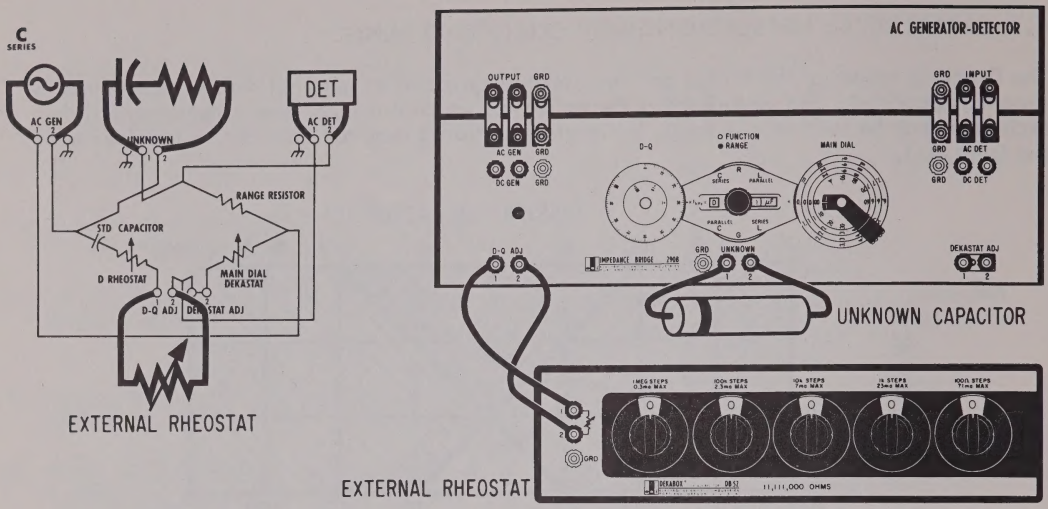


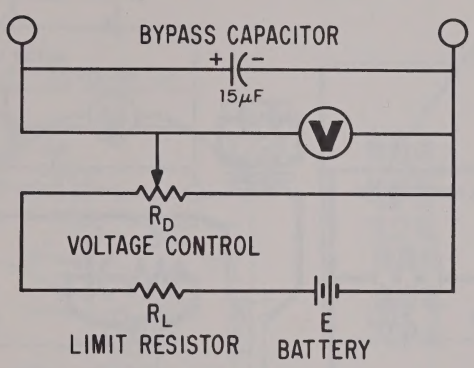
Figure 4-3. External D Rheostat

4.3 CAPACITANCE MEASUREMENT USING DC BIAS

Some capacitors need a polarizing voltage. Electrolytic and tantalum capacitors, for example, may give erroneous readings unless they are biased to prevent polarity reversal during test. Many electrolytic and tantalum capacitors can be damaged by the reverse half-cycle of an alternating current, although not generally by a low voltage level such as used in the Model 290B Impedance Bridge.

4.3.1 DC Bias Supply

The dc bias should be supplied from a power-limited source in order to prevent damage to the bridge in case the unknown capacitor terminals are shorted. The dc supply circuit is shown in Figure 4-4.



Supply Voltage E (volts)	Limiting Resistor R_L (ohms)	Voltage Control R_D (ohms)
1	0.27	2
1.5	0.56	5
2	1.0	10
3	2.7	25
4	4.7	40
4.5	5.6	50
6	10	100
9	22	250
12	39	400
15	56	500
22.5	150	1.5 k
24	150	1.5 k
28	220	2.5 k
30	270	2.5 k
45	560	3.0 k
67.5	1.2 k	10 k
90	2.2 k	20 k
103.5	2.7 k	30 k
120	3.9 k	50 k
225	13 k	100 k
300	27 k	250 k

Figure 4-4. DC Bias Supply Circuit

The power in the circuit shown is limited to 1 watt by resistor R_L. Values shown are for commonly available voltages. The limiting resistors can have tolerances of 20% and should be rated at 5 watts or more. If the proper value of resistance is not available, use a larger value rather than smaller. The voltage control potentiometer may differ from the listed value by a factor of 2. It should be rated at 1 watt or more.

If a supply voltage much different from those listed is to be used, use the following formula to determine the proper value of limiting resistance:

$$R_L = \frac{E^2}{4}\ ;\ R_D \approx 10R_L$$

Batteries are recommended because most line-operated power supplies have high leakage capacitance to ground and many have objectionably high dc leakage to ground.

For protection of the standard capacitor, do not use a voltage higher than 500 volts.

4.3.2 Operating Procedure

1. Set FUNCTION switch to C SERIES.

   With this setting, the standard capacitor and the unknown capacitor will block dc current from the other bridge arms.

2. Connect the unknown capacitor to UNKNOWN terminals.

   See Figure 4-5.

3. Remove shorting lug and connect dc bias supply, as shown in Figure 4-5.

4. Adjust dc voltage as required.

5. Measure capacitance.

   See Section 4.1 for the normal procedure.

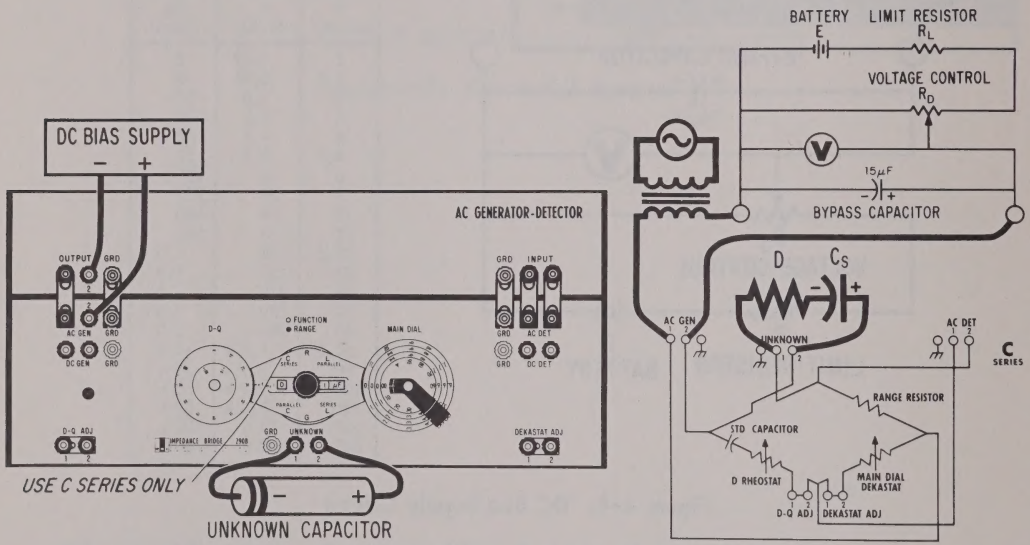


Figure 4-5. Capacitance Measurement Using DC Bias

4.4 VOLTAGE ACROSS UNKNOWN CAPACITOR

In many cases it is necessary to measure the ac voltage across a capacitor being tested. With the following procedure, the voltage can be measured with a high-impedance ac voltmeter without loading the capacitor under test.

1. Connect grounded terminal of ac voltmeter to AC DET terminal 1 and other terminal of the voltmeter to AC GEN terminal 2 (see Figure 4-6).
2. Balance the bridge and then read voltage on the voltmeter.

Since measuring voltage this way does not load the capacitor under test, the voltage will be correct. The capacitance reading of the bridge may be incorrect while the voltmeter is connected because the voltmeter may load the standard capacitor. For the correct capacitance reading, disconnect the voltmeter and rebalance the bridge.

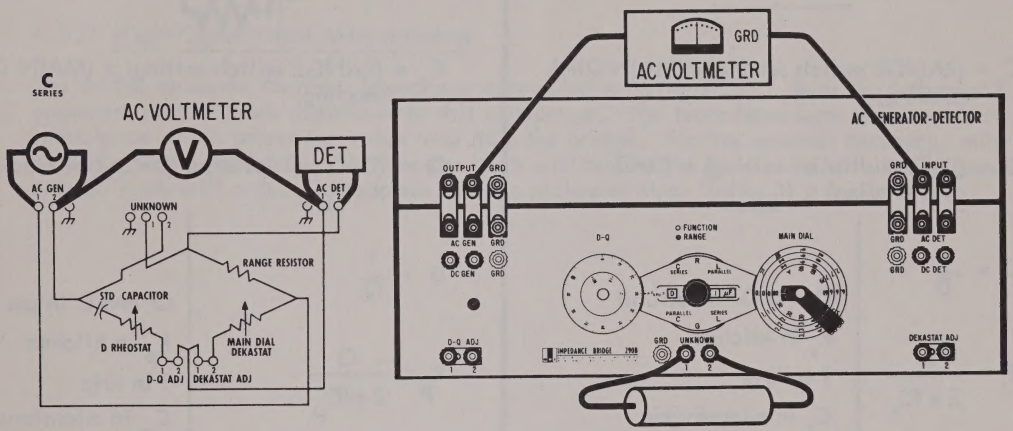


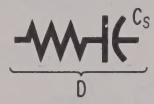
Figure 4-6. Voltage Across Unknown Capacitor

4.5 NOTES ON CAPACITANCE MEASUREMENT

4.5.1 Series and Parallel Capacitance

The bridge measures a simple equivalent circuit for the impedance connected to its terminals. This equivalent circuit consists of either a capacitance and resistance connected in series or a different capacitance and resistance connected in parallel. The phase and magnitude of the resulting impedance are identical for both circuits. For values of D greater than 0.01 the series and parallel capacitances differ measurably (by more than 0.01%).

WHEN THE BRIDGE MEASURES SERIES CAPACITANCE, C_s



C_s = (RANGE switch setting) x (MAIN DIAL reading)

D = (D-Q multiplier setting) x (D-Q dial reading) x (f_{kHz})

$$Q = \frac{1}{D}$$

$$R_s = \frac{D}{2\pi f C_s}$$

$$Z = \frac{D - j}{2\pi f C_s}$$

D and Q in per unit
R_s in kilohms
f in kHz
C_s in microfarads
$j = \sqrt{-1}$
Z in kilohms

To calculate the equivalent parallel circuit:

The D of the equivalent parallel circuit always equals the D of the equivalent series circuit. The same is true of Q.

$$C_p = \frac{C_s}{(1 + D^2)}$$

$$R_p = \frac{1}{D} \times \frac{1}{2\pi f C_p}$$

WHEN THE BRIDGE MEASURES PARALLEL CAPACITANCE, C_p

C_p = (RANGE switch setting) x (MAIN DIAL reading)

Q = (D-Q multiplier) x (D-Q dial reading) x (f_{kHz})

$$D = \frac{1}{Q}$$

$$R_p = \frac{Q}{2\pi f C_p}$$

$$Z = \frac{\frac{1}{Q} - j}{2\pi f C_p \left(1 + \frac{1}{Q^2}\right)}$$

Q and D in per unit
R_p in kilohms
f in kHz
C_p in microfarads
$j = \sqrt{-1}$
Z in kilohms

To calculate the equivalent series circuit:

The Q of the equivalent series circuit always equals the Q of the equivalent parallel circuit. The same is true of D.

$$C_s = \left(1 + \frac{1}{Q^2}\right) \times C_p$$

$$R_s = \frac{1}{Q} \times \frac{1}{2\pi f C_s}$$

4.5.2 Low-Capacitance Measurements

In making low-capacitance measurements, there are three things to watch out for:

1. Be careful to avoid pickup.

2. Keep the stray capacitance to a minimum.

3. Subtract the zero capacitance of the bridge from the dial reading.

To minimize the first two effects, keep hands as far as possible from the capacitor being measured. The zero capacitance of the bridge is measured with nothing connected to the UNKNOWN terminals; it is approximately 2 picofarads.

Keep the leads as short and direct as possible. If extended leads are necessary, the lead from terminal 2 should be shielded.

4.5.3 High-Capacitance Measurements

The bridge measures the total impedance connected to its terminals. Both the unknown capacitor and its leads contribute to this impedance. The leads have some resistance and inductance which affect the value read from the bridge. For the greatest accuracy, minimize the lead impedance. Short heavy leads will reduce the resistance and closely spaced, twisted leads will reduce inductance and the pickup of stray fields.

SECTION V

INDUCTORS

5.1 NORMAL INDUCTANCE MEASUREMENT

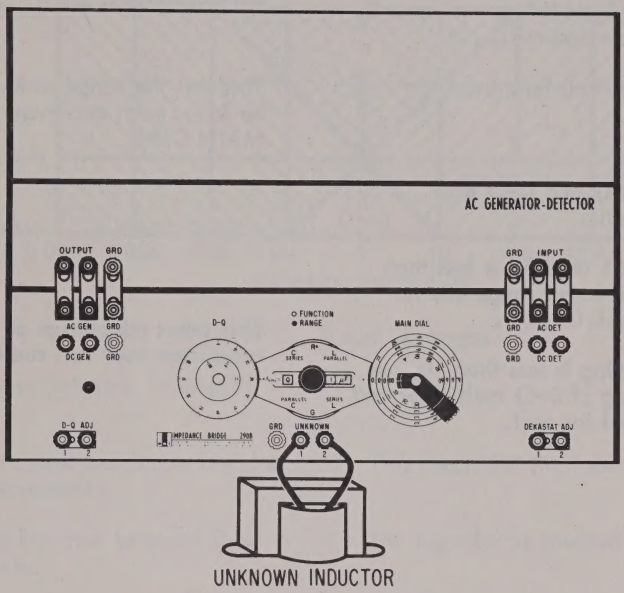


Figure 5-1. Normal Inductance Connection

1. Connect ac generator and detector.

   Connect the external generator and detector to the ac terminals. They will then be connected to the correct bridge circuits by the circuit selector.

> **CAUTION:** *Limit the generator output to one watt maximum. Recommended ESI AC Generators have this protective feature built in.*

2. Connect inductor to UNKNOWN terminals.

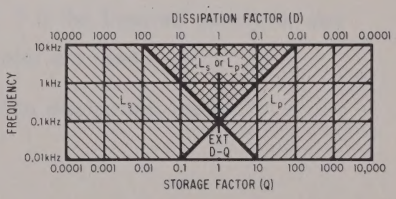
   Make good contact with the terminals.

3. Set FUNCTION selector to L_p or L_s

   At 1 kHz:

   Use L_p for Q greater than 0.1

   Use L_s for Q lower than 10



4. Set generator voltage and detector gain. See CAUTION, step 1.

5. Set MAIN DIAL to read 3.0000.

6. Set D-Q multiplier to .1x.

7. Set D-Q dial to 0, if bridge measures D, or 100, if bridge measures Q.

These settings make it easier to find the correct range.

8. Adjust RANGE switch for minimum detector signal.

This sets the range so that the value can be found with maximum resolution on the MAIN DIAL.

9. Adjust MAIN DIAL and D-Q dial alternately for null.

10. If the MAIN DIAL reading is less than 1.2000, use next lower range and readjust MAIN DIAL for null.

11. If D-Q dial reading is less than 10, use next lower setting of D-Q multiplier and readjust D-Q dial for null.

This takes advantage of the increased resolution near full scale of the dial.

5.2 INDUCTANCE MEASUREMENT WITH EXTENDED Q RANGE

The D and Q ranges of the bridge can be extended by use of an external rheostat connected to terminals provided. Figure 5-2 shows the range for which this technique is advisable.

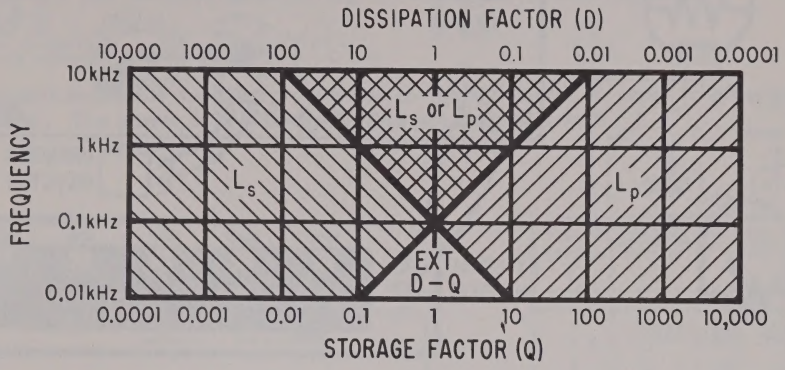


Figure 5-2. D and Q Ranges

1. Set FUNCTION switch to L PARALLEL or L SERIES.

2. Turn D-Q dial to zero and leave it there during the measurement.
   This shorts out the internal D-Q rheostat.

3. Remove shorting lug from between D-Q ADJ binding posts.
   The lug may be pivoted to one side.

4. Connect an external rheostat between D-Q ADJ binding posts.
   See Figure 5-3.

5. Balance the bridge using external rheostat instead of D-Q dial.
   The measured inductance is the product of the MAIN DIAL setting times the setting of the RANGE control.

6. Calculate Q or D.

$$Q = \frac{1.592}{f_k \; R_k}$$

$$D = \frac{f_k \; R_k}{1.592}$$

Q is the storage factor.

f_k is the frequency in kilohertz.

R_k is the resistance in kilohms of the external Q rheostat.

f_k = 1 if the internal generator and detector are used.

D is the dissipation factor.

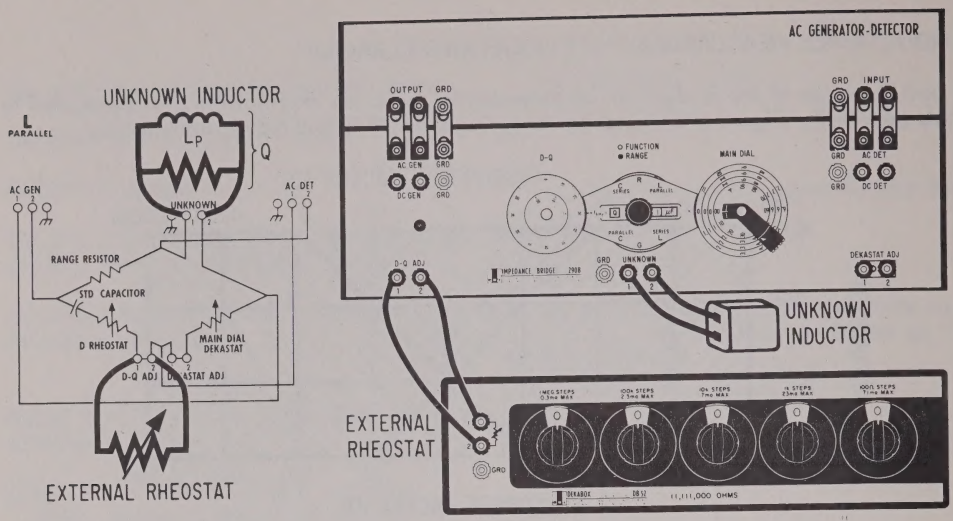


Figure 5-3. Parallel Inductance, External Q Rheostat

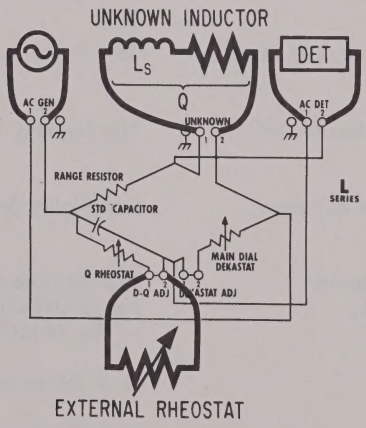


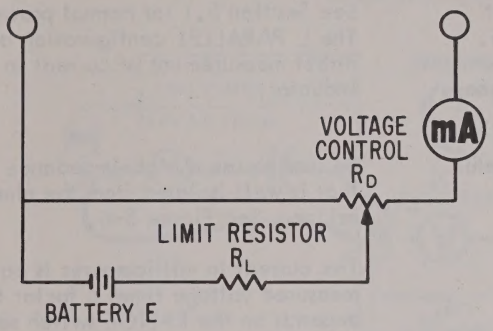
Figure 5-4. Series Inductance, External Q Rheostat

5.3 INDUCTANCE MEASUREMENT USING DC

Iron-core inductors are sensitive to both ac and dc current variations. Quantitative measurements of dc effects can be made by supplying current to the unknown inductor.

5.3.1 DC Supply

The dc current should be supplied from a power-limited source in order to prevent damage to the bridge. The power to the bridge should not exceed 1 watt.



Supply Voltage E (volts)	Limiting Resistor R_L (ohms)	Voltage Control R_D (ohms)
1	10	100
1.5	15	150
2	22	250
3	33	250
4	47	500
4.5	47	500
6	68	750
9	100	1 k
12	120	1.5 k
15	150	1.5 k
22.5	270	2.5 k
24	270	2.5 k
28	330	3.5 k
30	330	3.5 k
45	560	5 k
67.5	1.2 k	10 k
90	2.2 k	20 k
103.5	2.7 k	30 k
120	3.9 k	50 k
225	13 k	100 k
300	27 k	250 k

Figure 5-5. DC Supply Circuit

The dc supply circuit shown in Figure 5-5 is safe at any bridge setting. Other values of voltage, limiting resistor (R_L) and voltage control (R_D) are given in the table. Values shown are for commonly available voltages. The limiting resistors can have tolerances of 20% and should be rated at 5 watts or more. If the proper value of resistor is not available, use a larger value rather than smaller. The voltage control potentiometer may differ from the listed value by a factor of 2. It should be rated at 1 watt or more.

If a supply voltage much different from those listed is to be used, use the following formulas to determine the proper value of limiting resistance:

$$R_L = \frac{E^2}{4}; \quad R_D \approx 10R_L$$

Batteries are recommended because most line-operated power supplies have high leakage capacitance to ground and many have objectionably high dc leakage to ground. To protect the standard capacitor, do not use a voltage higher than 500 volts.

5.3.2 Operating Procedure

1. Set FUNCTION switch to L PARALLEL or L SERIES.

   The L PARALLEL setting is preferred since in this bridge configuration, the standard capacitor blocks dc current and allows direct measurement of current through the inductor.

2. Connect the unknown inductor to UNKNOWN terminals.

   See Figure 5-6.

3. Remove shorting lug and connect dc bias between generator and AC GEN terminal 2.

   See Figure 5-6.

4. For L PARALLEL: Adjust dc current as required and measure inductance. For L SERIES: Set current to approximately the desired level and balance the bridge for a first approximation.

   See Section 5.1 for normal procedure. The L PARALLEL configuration allows direct measurement of current in the inductor.

5. For L SERIES: Connect a dc voltmeter between AC GEN terminal 2 and UNKNOWN terminal 1.

   Be sure to use a high-impedance voltmeter that is well isolated from the chassis of the bridge. See Figure 5-6.

6. For L SERIES: Alternately adjust the bridge for balance and adjust the current for the desired level.

   The current in milliamperes is equal to the measured voltage times a factor that depends on the RANGE switch setting. The following table lists the multipliers.

RANGE Setting	Multiplier
10^{-4}	1000
10^{-3}	100
10^{-2}	10
10^{-1}	1.0
1	0.1
10	0.01
100	0.001

7. For L SERIES: When the correct current is flowing at the same time the bridge is balanced, disconnect the voltmeter and rebalance the bridge.

   The indicated current is correct, but there may be an error in measured inductance when the voltmeter is connected because it may load the range resistor.

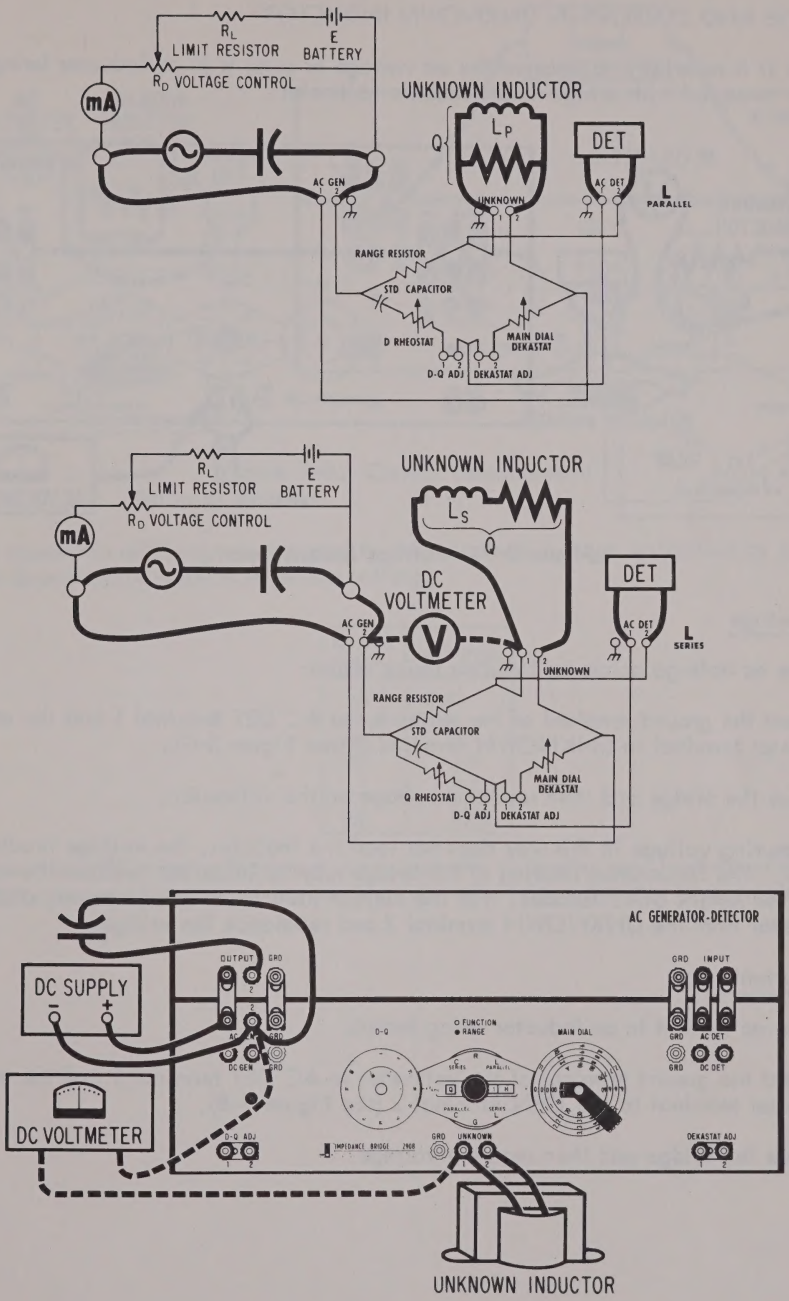


Figure 5-6. Inductance Measurement Using DC

5.4 VOLTAGE AND CURRENT IN UNKNOWN INDUCTOR

In many cases it is necessary to measure the ac voltage or current in an inductor being tested. Either can be measured with a high-impedance ac voltmeter.

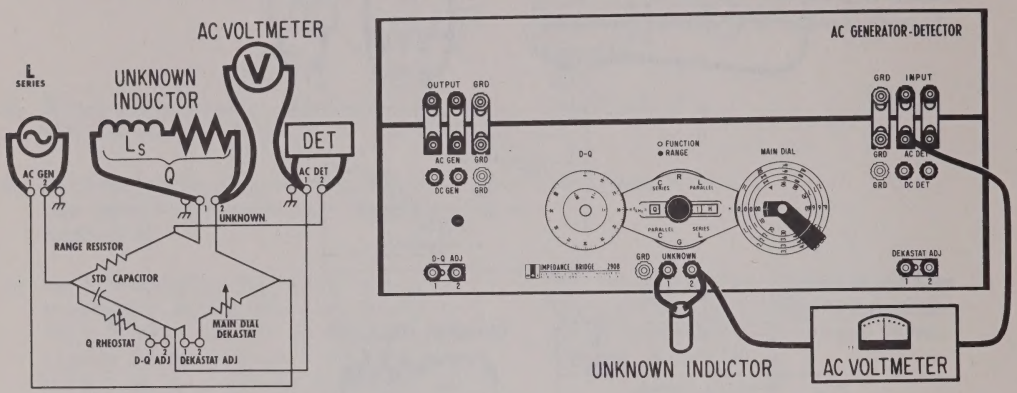


Figure 5-7. Voltage Measurement

5.4.1 Voltage

To measure ac voltage across an inductor being tested:

1. Connect the ground terminal of the voltmeter to AC DET terminal 1 and the other voltmeter terminal to UNKNOWN terminal 2 (see Figure 5-7).

2. Balance the bridge and *then* read the voltage on the voltmeter.

Since measuring voltage in this way does not load the inductor, the voltage reading will be correct. The inductance reading of the bridge may be incorrect because the voltmeter may load the MAIN DIAL decades. For the correct inductance measurement, disconnect the voltmeter from the UNKNOWN terminal 2 and rebalance the bridge.

5.4.2 Current

To measure ac current in an inductor being tested:

1. Connect the ground terminal of the voltmeter to AC DET terminal 1 and the other voltmeter terminal to AC GEN terminal 2 (see Figure 5-8).

2. Balance the bridge and *then* read the voltage.

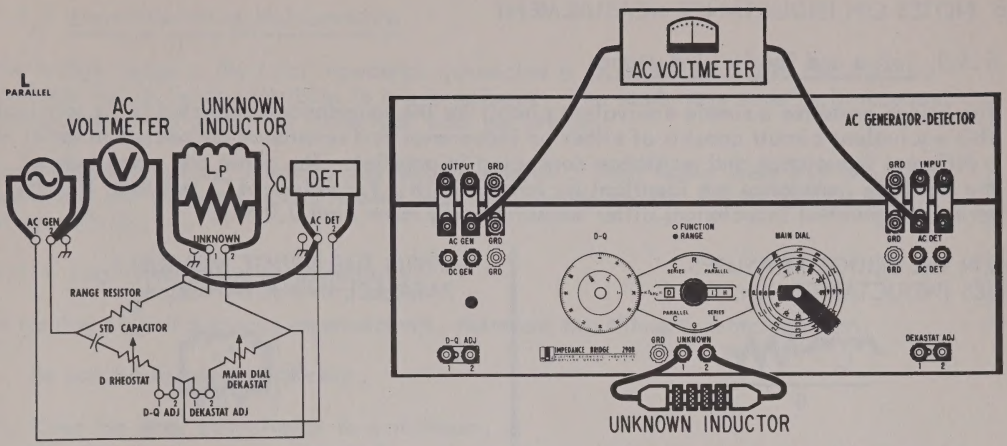


Figure 5-8. Current Measurement

3. The current in milliamperes is equal to the measured voltage multiplied by a factor that depends on the RANGE switch setting.

RANGE Setting	Multiplier
10^{-4}	1000
10^{-3}	100
10^{-2}	10
10^{-1}	1.0
1	0.1
10	0.01
100	0.001

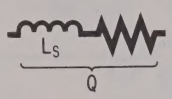
The current in milliamperes is correct, but since the voltmeter may load the standard capacitor, the measured inductance may be incorrect when the voltmeter is connected.

5.5 NOTES ON INDUCTANCE MEASUREMENT

5.5.1 Series and Parallel Inductance

The bridge measures a simple equivalent circuit for the impedance connected to its terminals. This equivalent circuit consists of either an inductance and resistance connected in series or a different inductance and resistance connected in parallel. The phase and magnitude of the resulting impedance are identical for both circuits. For values of Q less than 100 the series and parallel inductances differ measurably (by more than 0.01%).

WHEN THE BRIDGE MEASURES SERIES INDUCTANCE, L_s:



L_s = (RANGE switch setting) x (MAIN DIAL reading)

Q = (D-Q multiplier setting) x (D-Q dial reading) x (f_{kHz})

$D = \frac{1}{Q}$

$R_s = \frac{1}{Q} \times 2\pi f L_s$

$Z = 2\pi f L_s \left(\frac{1}{Q} + j\right)$

Q and D in per unit
R_s in kilohms
f in kHz
L_s in henrys
$j = -1$
Z in kilohms

To calculate the equivalent parallel circuit:

The Q of the equivalent parallel circuit always equals the Q of the equivalent series circuit. The same is true of D.

$L_p = \left(1 + \frac{1}{Q^2}\right) \times L_s$

$R_p = Q \times 2\pi f L_p$

WHEN THE BIRDGE MEASURES PARALLEL INDUCTANCE, L_p:

L_p = (RANGE switch setting) x (MAIN DIAL reading)

D = (D-Q multiplier setting) x (D-Q dial reading) x (f_{kHz})

$Q = \frac{1}{D}$

$R_p = \frac{1}{D} \times 2\pi f L_p$

$Z = \frac{2\pi f L_p (D + j)}{D^2 + 1}$

D and Q in per unit
R_p in kilohms
f in kHz
L_p in henrys
$j = -1$
Z in kilohms

To calculate the equivalent series circuit:

The D of the equivalent series circuit always equals the D of the equivalent parallel circuit. The same is true of Q.

$L_s = \frac{1}{1 + D^2} \times L_p$

$R_s = D \times 2\pi f L_s$

5.5.2 Low-Inductance Measurements

The bridge measures the total impedance connected to its terminals. Both the unknown inductor and its leads contribute to this impedance. The leads have some resistance and inductance which affect the value read from the bridge.

For greatest accuracy, minimize the lead impedance. Short heavy leads will reduce the resistance and closely spaced, twisted leads will reduce the inductance and the pickup of stray fields.

5.5.3 High-Inductance Measurements

In making high-inductance measurements, there are two things to watch out for:

1. Be careful to avoid ac pickup.

2. Keep the stray capacitance to a minimum.

To minimize both effects keep hands as far as possible from the inductor measured. Keep the leads as short and direct as possible. If extended leads are necessary, the lead from terminal 2 should be shielded. Take care to avoid coupling stray magnetic fields into the inductor being measured.

SECTION VI

USEFUL MEASUREMENT TECHNIQUES

6.1 SLIDING BALANCE

When lossy capacitors and inductors are measured, the nulling problem known as sliding balance can occur. This problem is most frequently encountered in inductors. It is not too serious if the Q of an inductor is greater than 1 or if the D of a capacitor is less than 1. In either case, an external D-Q rheostat may be necessary.

The problem becomes apparent when the instrument seems to have false nulls at different settings of the MAIN DIAL and the D-Q dial. Figure 6-4 illustrates the cause of the difficulty.

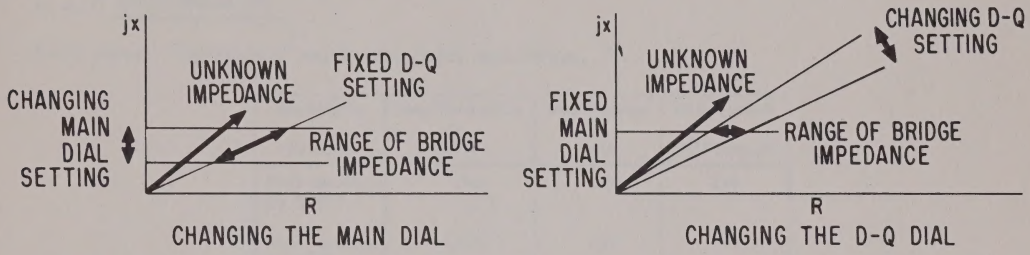


Figure 6-1. Sliding Balance

If the unknown impedance and the bridge impedance are considered as vectors, the bridge is balanced when the vectors are equal. The MAIN DIAL changes the vector of the bridge impedance only along the R axis, and the D-Q dial changes the angle of the vector of the bridge impedance. If the angle of the unknown impedance vector is not steep, the MAIN DIAL and the D-Q dial operate nearly perpendicular to each other and there is little or no difficulty. (This is the case of low D or high Q.)

If the D of a capacitor is high or the Q of an inductor is low, the vector of the unknown impedance has such a steep angle that the dials no longer move the bridge impedance vector directly to a null.

The following technique will allow rapid and accurate measurements with sliding balance.

1. Make a preliminary measurement using the techniques described in Section 4.1 for capacitors, Section 5.1 for inductors.	This gives a first approximation. The null at this point may not be very sharp.
2. Adjust detector gain so that meter pointer is on a recognizable point at about half-scale.	This sets a reference level on the detector. As the null comes closer, use marks closer to 0.
3. Turn the inner MAIN DIAL a small amount in one direction, then adjust D-Q dial for minimum detector deflection.	Turn one switch step of the outer dial at first. Use smaller steps when the null is close.

4. Note the reading on the meter. If it is closer to 0, repeat steps 2 and 3, turning MAIN DIAL in the same direction. If the reading is further from 0, repeat steps 2 and 3, turning MAIN DIAL in the opposite direction.

This procedure should converge to a sharp null. Each step should be shorter than the last when the null is close.

5. When the null is close, turn the D-Q dial part of a dial division at a time and adjust MAIN DIAL for best null.

Watch out for false nulls at the ends of the range of the instrument, especially at low settings of the series inductive circuit. When the D-Q dial and the MAIN DIAL are both at zero in the series inductive circuits, the generator is short circuited and the bridge indicates null.

6.2 BRIDGE ELEMENT VOLTAGE AND CURRENT LIMITS

6.2.1 Range Resistors

Resistance in Ohms	Max Voltage in Volts	Max Current in Milliamperes
1	0.71	710.00
10	2.30	230.00
100	7.10	71.00
1,000	23.00	23.00
10,000	71.00	7.10
100,000	230.00	2.30
1,000,000	250.00	0.25

6.2.2 D-Q Rheostats

Safe power limited to 7 watts into total resistance.

Resistance in Kilohms	Max Resistance in Ohms	Max Voltage in Volts	Max Current in Milliamperes
D-Q Reading x0.01592	166	35	210
D-Q Reading x0.1592	1,670	110	68
D-Q Reading x1.5920	16,750	350	21

6.2.3 Standard Resistor

Safe power limited to 1/2 watt.

Resistance in Ohms	Max Voltage in Volts	Max Current in Milliamperes
10,000	71	7.1

6.2.4 Main Dial Rheostat

Safe power limited to 1/2 watt per step.

Decade	Resistance in Ohms	Max Voltage in Volts per Step	Max Current in Milliamperes
First	1000Ω steps	23	23
Second	100Ω steps	7.1	71
Third	10Ω steps	2.3	230
Rheostat	0 - 10.5Ω	2.3 at max	230

SECTION VII

MAINTENANCE

7.1 PARTS LIST

The following parts list is in alpha-numerical order of the circuit reference designator. Miscellaneous parts are included at the end of the list. Manufacturer of the part is given in a code number according to the Federal Supply Code for Manufacturers; see list of manufacturers below. Parts recommended as spares to sustain operation in isolated locations are indicated in the recommended spare parts column.

Parts manufactured by Electro Scientific Industries must be ordered from the factory. When ordering parts from the factory include the following information:

Model and serial number of the instrument
Electro Scientific Industries part number
Circuit reference designator
Description of part

CODE LIST OF MANUFACTURERS

11837	ELECTRO SCIENTIFIC INDUSTRIES Portland, Oregon
56289	SPRAGUE ELECTRIC CO. North Adams, Massachusetts
65092	WESTON INSTRUMENTS DIVISION OF DAYSTROM, INC. Newark, New Jersey
80583	HAMMARLUND CO., INC. New York, New York
84171	ARCO ELECTRONICS INC. Great Neck, New York

Ckt Ref	Description	Mfr Code	ESI Part No.	Qty Used	Recm Spares
A1	Assy, DEKASTAT	11837	3215	1	1
A2	Assy, Multiplier Function	11837	3298	1	1
A3	Assy, D-Q Rheostat	11837	3211	1	1
C1	Capacitor, Std 0.1μ F	11837	18641	1	1
C2	Capacitor, Variable, 6.3 -140pF Mfr PN APC - 140-C	80583	3385	1	

Ckt Ref	Description	Mfr Code	ESI Part No.	Qty Used	Recm Spares
C3	Capacitor, Fixed, 0.47 μF ±10%, Subminiature Metal Clad Mfr PN 178P479153, Part of Assy A2	56289	2178	1	
C4	Capacitor, Fixed, 0.022 μF ±10%, Black Beauty Mfr PN 109P22342, Part of Assy A2	56289	2174	1	
C5	Capacitor, Fixed, 7500pF ±1%, Mica, Mfr PN CM35E752F, Part of Assy A2	84171	2162	1	
C6	Capacitor, Fixed, 800pF ±5%, Mica, Mfr PN CM20D8015, Part of Assy A2	84171	2153	1	
C7	Capacitor, Fixed, 68pF ±5%, Mica, Mfr PN CM15E680J, Part of Assy A2	84171	2133	1	
R1	Resistor, Fixed, Precision, 1kΩ, Part of Assy A1	11837	*	1	*
R2,3,4, 5,6	Resistor, Fixed, Precision, 2kΩ, Part of Assy A1	11837	*	5	*
R7	Resistor, Fixed, Precision, 100Ω, Part of Assy A1	11837	*	1	*
R8,9,10, 11,12	Resistor, Fixed, Precision, 200Ω, Part of Assy A1	11837	*	5	*
R13	Resistor, Fixed, Precision, 10Ω, Part of Assy A1	11837	*	1	*
R14,15, 16,17,18	Resistor, Fixed, Precision, 20Ω, Part of Assy A1	11837	*	5	*
R19	Resistor, Variable, 10.5Ω, Part of Assy A1	11837	*	1	*
R20	Resistor, Fixed, Precision, 10kΩ, Part of Assy A2	11837	*	1	*
R21	Resistor, Variable, 159.2Ω, Part of Assy A3	11837	*	1	*
R22	Resistor, Variable, 1592Ω, Part of Assy A3	11837	*	1	*
R23	Resistor, Variable, 1592Ω, Part of Assy A3	11837	*	1	*
R24	Resistor, Fixed, Precision, 1Ω, Part of Assy A2	11837	*	1	*
R25	Resistor, Fixed, Precision, 10Ω, Part of Assy A2	11837	*	1	*

*Replace entire assembly

Ckt Ref	Description	Mfr Code	ESI Part No.	Qty Used	Recm Spares
R26	Resistor, Fixed, Precision, 100Ω, Part of Assy A2	11837	*	1	*
R27	Resistor, Fixed, Precision, 1kΩ, Part of Assy A2	11837	*	1	*
R28	Resistor, Fixed, Precision, 10kΩ, Part of Assy A2	11837	*	1	*
R29	Resistor, Fixed, Precision, 100kΩ, Part of Assy A2	11837	*	1	*
R30	Resistor, Fixed, Vamistor, 990kΩ, Mfr PN 9852, Part of Assy A2	65092	2001	1	*
R31	Resistor, Fixed, Select to Adjust R30, Part of Assy A2			1	*
S1,2,3	Switch, Part of Assy A1	11837	*	3	*
S4	Switch, Part of Assy A2	11837	*	1	*
S5	Switch, Part of Assy A2	11837	*	1	*
S6	Switch, Part of Assy A3	11837	*	1	*
	Miscellaneous				
	Binding Post	11837	1393	19	
	Cap, Binding Post, Black	11837	1170	14	4
	Cap, Binding Post Metal	11837	1172	5	2
	Cover, Dust	11837	3347	1	
	Dial, D-Q	11837	2780	1	
	Dial, D-Q Multiplier	11837	3346	1	
	Dial, FUNCTION	11837	3242	1	
	Dial, MAIN DIAL 1st	11837	4275	1	
	Dial, MAIN DIAL 2nd	11837	3332	1	
	Dial, MAIN DIAL 3rd	11837	3333	1	
	Dial, MAIN DIAL Rheostat	11837	3344	1	
	Dial, RANGE	11837	3243		
	Insulator, Binding Post	11837	8823	8	
	Knob	11837	1255	1	
	Mask	11837	3375	1	
	Shield, Binding Post	11837	3295	1	
	Shield, Cover	11837	3331	1	
	Swing Lug	11837	3247	2	

*Replace entire assembly

7.2 BRIDGE CIRCUIT DIAGRAMS

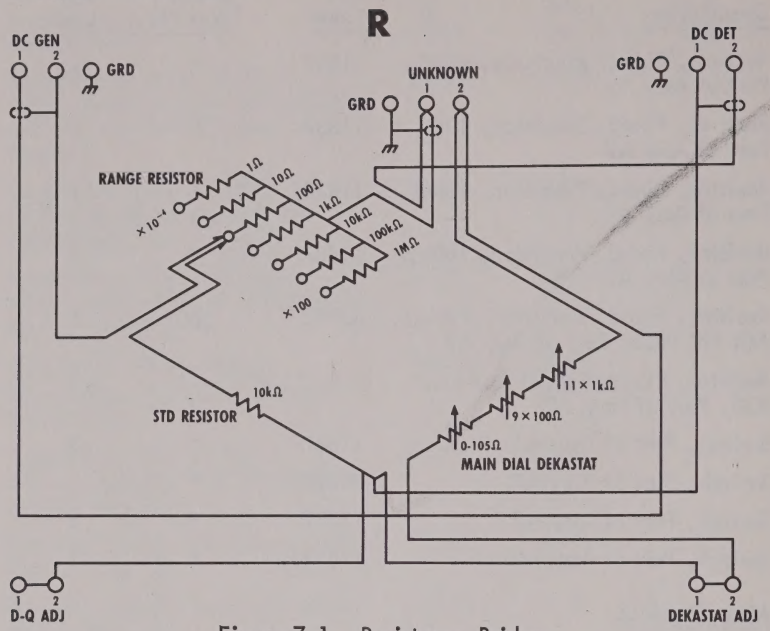


Figure 7-1. Resistance Bridge

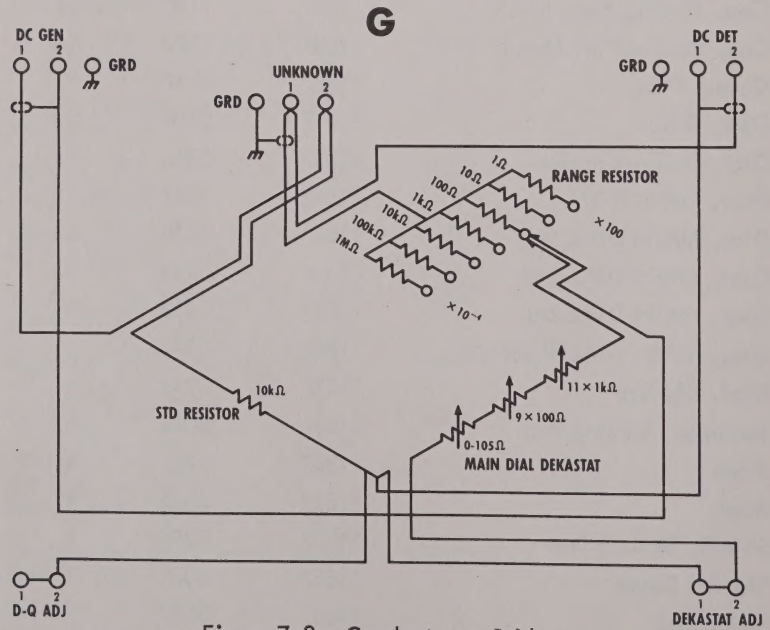


Figure 7-2. Conductance Bridge

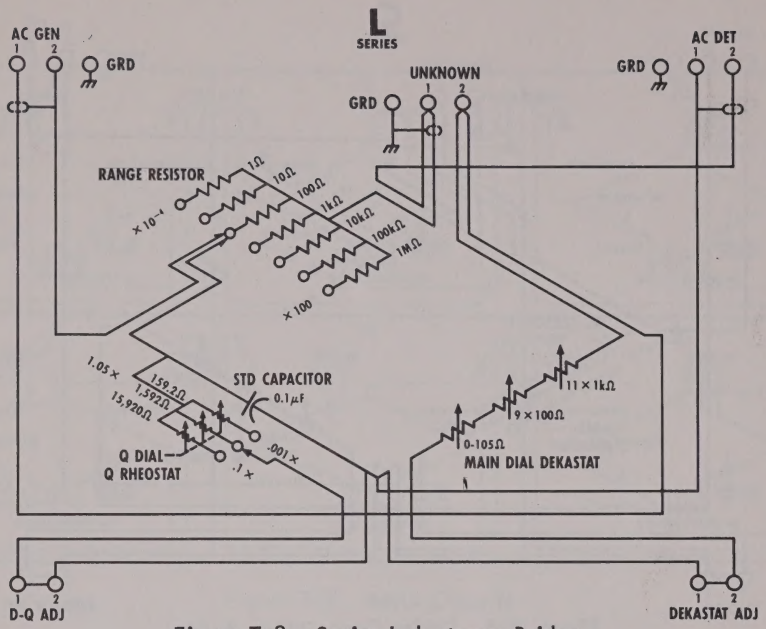


Figure 7-3. Series Inductance Bridge

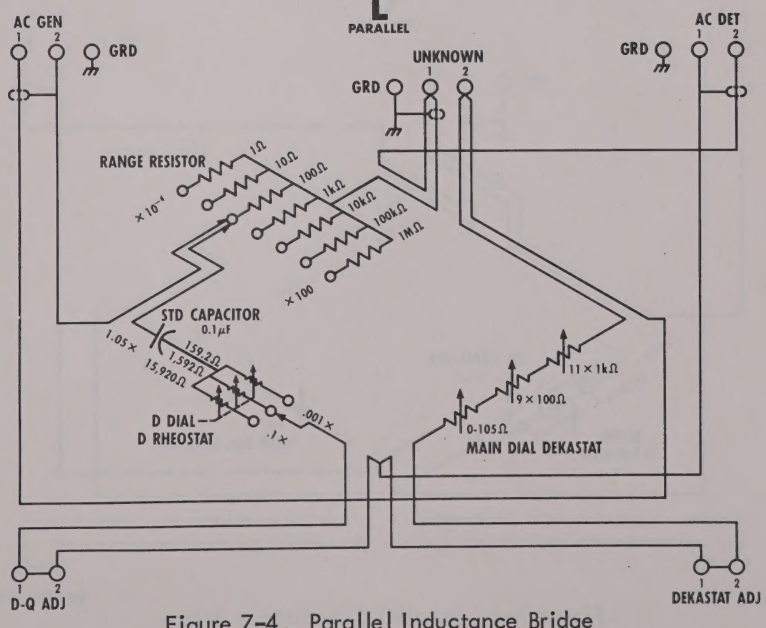


Figure 7-4. Parallel Inductance Bridge

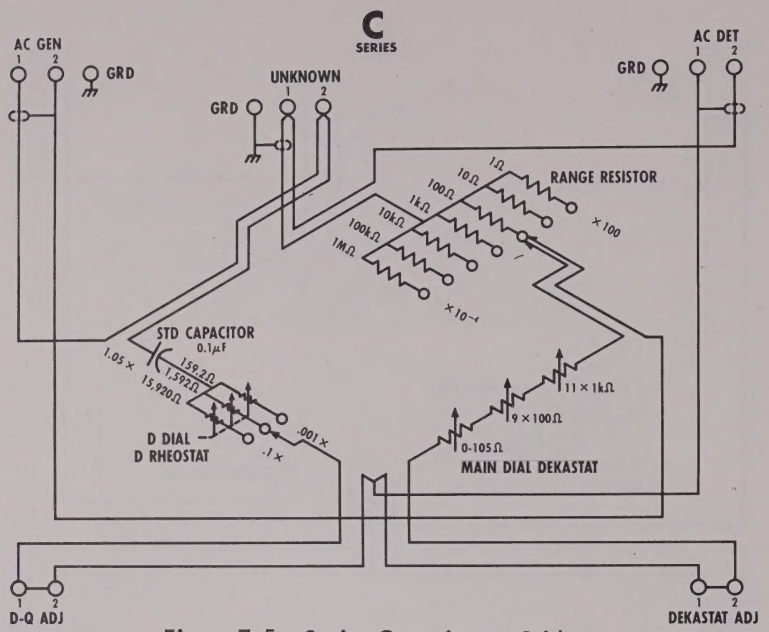


Figure 7-5. Series Capacitance Bridge

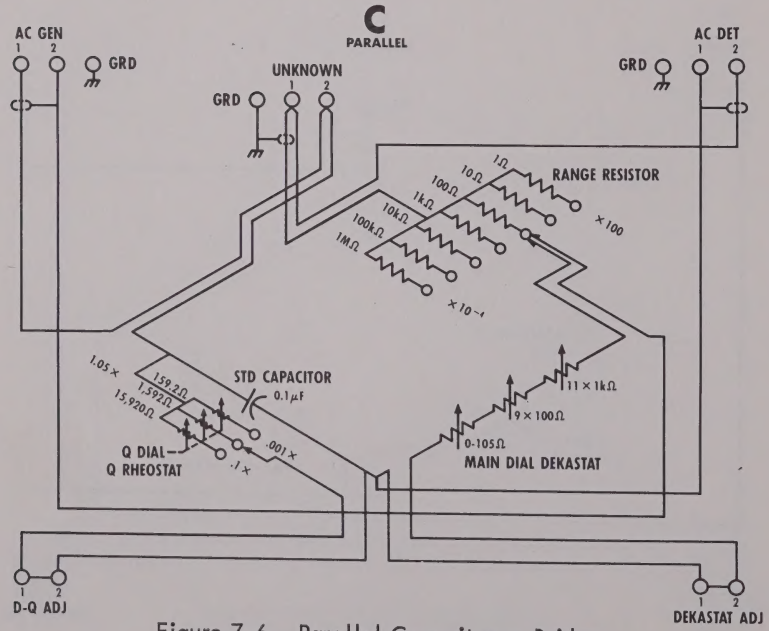


Figure 7-6. Parallel Capacitance Bridge

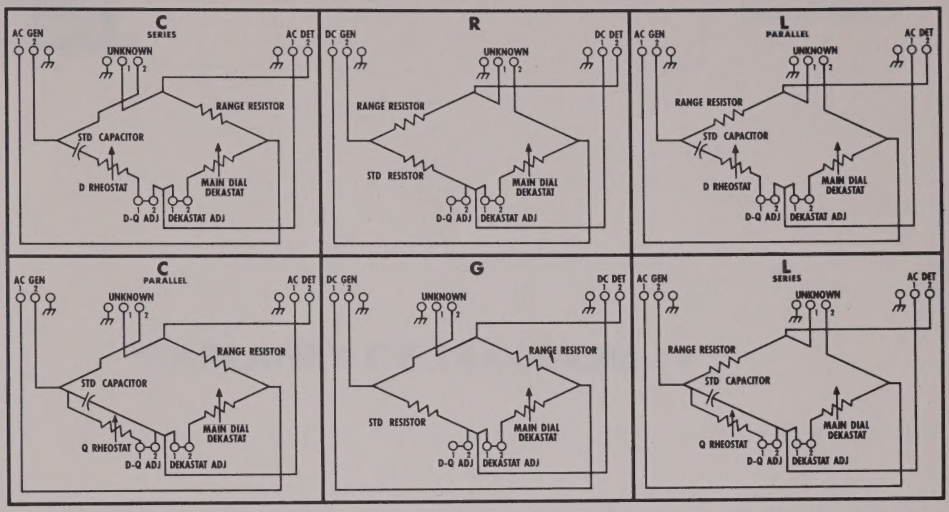


Figure 7-7. Basic Circuits

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EB44 **DC Measurements Using Ratio Techniques,** *Jack C. Riley, September 1965*

TA2 **A Ratio Transformer Bridge for Standardization of Inductors and Capacitors,** *D. L. Hillhouse and H. W. Kline, August 1960*

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